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SINGLE WALL PENETRATION EQUATIONS

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   This report compares five single plate penetration equations for accuracy and effectiveness. These five equations are two well-known equations (Fish-Summers and Schmidt-Holsapple), two equations developed for the Apollo project (Rockwell and Johnson Space Center (JSC)), and one recently revised from JSC (Cour-Palais). They were derived from test results, with velocities ranging up to 8 km/s. Microsoft Excel software was used to construct a spreadsheet to calculate the diameters and masses of projectiles for various velocities, varying the material properties of both projectile and target for the five single plate penetration equations. The results were plotted on diameter versus velocity graphs for ballistic and spallation limits using Cricket Graph software, for velocities ranging from 2 to 15 km/s defined for the orbital debris. First, these equations were compared to each other, then each equation was compared with various aluminum projectile densities. Finally, these equations were compared with test results performed at JSC for the Marshall Space Flight Center. These equations predict a wide range of projectile diameters at a given velocity. Thus, it is very difficult to choose the "right" prediction equation. The thickness of the single plate could have a large variation by choosing a different penetration equation. Even though all five equations are empirically developed with various materials, and especially for aluminum alloys, one cannot be confident in the shield design with the predictions obtained by the penetration equations without verifying by tests.

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TECHNICAL MEMORANDUM

SINGLE WALL PENETRATION EQUATIONS

1.   INTRODUCTION

Concern about the effects of orbital debris impacts on space vehicles in low-Earth orbit has prompted a study of penetration predictor equations for a single plate structure. Since the mid-60's, many equations have been developed to predict penetration of a single thin plate by a meteoroid or orbital debris projectile. This document is a report of a comparison of five of these equations for accuracy and effectiveness.

Each equation included in this study was developed with a unique set of test parameters. Actual conditions under which a spacecraft is required to survive may or may not be within the parameter range for an equation. Therefore, extreme care should be taken when using any predictor equation since each can only be used to predict penetration for a specific set of parameters. After some study of test parameters, it will become obvious that the majority of expected projectile velocities cannot be tested with current technology. Theoretical predictions must be relied upon for these occurrences until further advances can be made in hypervelocity impact technology.

It is not the purpose of this report to recommend the correct equations to use in analyzing a vehicle, but rather to compare the equations and how they were developed to give the designer a better feel for how the design will stand up to hypervelocity impacts of orbital debris projectiles. Hypervelocity impact testing should always be included in the design/verification schedule for any vehicle which will be exposed to the orbital debris environment for any length of time.

One should not neglect to analyze a vehicle which has potential safety problems. Each component should be carefully evaluated to discover possible dangerous effects of hypervelocity impacts. A

vehicle should have an acceptable reliability for astronaut safety as well as an acceptable reliability for no functional failure.

2. SINGLE PLATE PENETRATION EQUATIONS

Two well-known equations (Fish-Summers and Schmidt-Holsapple), two equations developed for the Apollo project (Rockwell and Johnson Space Center (JSC)), and one recently revised from JSC (Cour-Palais) are the five single plate penetration equations compared in this section for accuracy and effectiveness. The following subsections will discuss each of these empirical equations.

2.1 Fish-Summers Equation

The following equation was developed by Fish and Summers.[1] They used test results with velocities which ranged from 0.5 to 8.5 km/s, metallic targets which ranged in density from a magnesium-lithium alloy to a beryllium-copper alloy, and with aluminum alloy projectiles.[2] This equation was recommended for design to establish the threshold penetration (ballistic limit) of thin, ductile, metal plates.

$$t = K_1 m^{0.352} V^{0.875} \rho^{\frac{1}{6}}$$

where

t = target thickness (cm)
K_1 = a constant for target
m = projectile mass (gm)
ρ = projectile density (gm/cm^3)
V = impact velocity (km/s)

 and

K_1 = 0.57 for aluminum alloys such as 2024-T3, 2024-T4, 6061-T6, and 7075-T6.

Additional values for K_1 are given in the reference.

The 0.70 factor was used to determine the plate thickness to prevent a penetration from spalling (spallation limit), as recommended by Coronado, Gibbins, Wright, and Stem.[3]

The Fish-Summers equation is the simplest of all the equations presented here. Target material properties effects are taken care of by the constant K_1.

2.2   Schmidt-Holsapple Equation

The following equation was developed by Holsapple and Schmidt,[4] with test results obtained by many investigators such as Payne, Gault, Wedekind, et al. Some tests done by Payne used projectiles of tungsten, carbide, lead, copper, stainless steel, titanium, magnesium and aluminum; targets of stainless steel and aluminum; and velocities ranging from 4 to 8 km/s. Some tests done by Gault used Pyrex spheres as the projectiles, water as the target, and velocities ranging from 1.5 to 6.0 km/s.[3]

$$d = 2.06t \left(\frac{\rho_P}{\rho_t} \right)^{-0.159} \left(\frac{2.68 F_{tu}}{\rho_P V_n^2} \right)^{0.236} ,$$

where

    d = projectile diameter (in)

    t = target thickness (in)

    ρ_p = projectile density (lb/in^3)

    ρ_t = target density (lb/in^3)

    F_{tu} = ultimate tensile strength for target (lb/in^2)

    V_n = impact velocity (normal component of the projectile relative velocity) (ft/s).

Again the 0.70 factor was used for the spallation limit.

The Schmidt-Holsapple equation involves the target material strength and density as well as projectile density to better characterize the material behavior of impact. This is the only equation of those presented in this paper using English units.

2.3 Rockwell Equation for the Apollo Project

There were two independently developed empirical equations for the Apollo project. One was developed by Rockwell and the other by Burton Cour-Palais at JSC.[5] The Rockwell equation shown below was developed from test results using aluminum projectiles and targets with impact velocities up to 8 km/s. The JSC (Cour-Palais) equation will be discussed in subsection 2.4.

For crater depth:

$$p = 1.38d^{1.1}BH^{-0.25}\rho_P^{0.5}\rho_t^{-0.167}V^{0.67}$$

For ballistic limit:
$$t_b = 1.8p,$$

For spallation limit:
$$t_s = 3.0p,$$

where:

p = crater depth on target (cm)

t_b = target thickness for ballistic limit (cm)

t_s = target thickness for spallation limit (cm)

d = projectile diameter (cm)

ρ_P = projectile density (gm/cm^3)

ρ_t = target density (gm/cm^3)

BH = Brinnell hardness for target

V = impact velocity (km/s).

This equation involves target density and material hardness as well as projectile density to characterize the behavior of impacts.

2.4 JSC (Cour-Palais) Equation for the Apollo Project

As mentioned in the previous section, NASA/JSC engineers developed the equation shown below during the Apollo project, independent of the Rockwell equation but in appearance very similar.[5]

For crater depth with projectile density $\left(\dfrac{\rho_P}{\rho_t} < 1.5\right)$:

$$p = 5.24d^{1.056} BH^{-0.25} \rho_P^{0.5} \rho_t^{-0.167} E^{-0.33} V^{0.67}$$

For ballistic limit:

$$t_b = 2.0p.$$

For spallation limit:
$$t_s = 3.0p,$$

where:

p = crater depth on target (cm)

t_b = target thickness for ballistic limit (cm)

t_s = target thickness for spallation limit (cm)

d = projectile diameter (cm)

ρ_P = projectile density (gm/cm^3)

ρ_t = target density (gm/cm^3)

BH = Brinnell hardness for target

E = Young's modulus for target (GPa)

V = impact velocity (km/s).

This equation involves target density, the modulus of elasticity, and material hardness as well as projectile density to characterize the behavior of impacts.

2.5 JSC (Modified Cour-Palais) Equation

The newest and recently distributed equation modified from the Cour-Palais equation for the Apollo project by Burton Cour-Palais at JSC is shown below.[6]

For crater depth:

$$p = 5.24 \, d^{\frac{19}{18}} \, BH^{-0.25} \left(\frac{\rho_P}{\rho_t}\right)^{0.5} \left(\frac{V_n}{C}\right)^{\frac{2}{3}}$$

For ballistic limit

$$t_b = 1.8p.$$

For spallation limit:
$$t_s = 2.2p,$$

where:

$p =$ crater depth on target (cm)

$t_b =$ target thickness for ballistic limit (cm)

$t_s =$ target thickness for spallation limit (cm)

$d =$ projectile diameter (cm)

$\rho_p =$ projectile density (gm/cm^3)

$\rho_t =$ target density (gm/cm^3)

$BH =$ Brinnell hardness for target

$V_n =$ impact velocity (normal component of the projectile relative velocity) (km/s).

$C =$ speed of sound for target (km/s)

$$= \sqrt{\frac{E}{\rho_t}} \, .$$

This equation uses dimensionless quantities by making ratios of target and projectile densities and velocities.

3.   COMPARISONS OF FIVE SINGLE PLATE PENETRATION EQUATIONS AND TEST RESULTS

The comparison of the five equations discussed in section 2 will be discussed in subsection 3.1. Then the comparison of these equations with test results will be discussed in subsection 3.2.

3.1   Comparisons of Single Plate Penetration Equations

Microsoft Excel software was used to construct a spreadsheet to calculate the diameters and masses of projectiles for various velocities, varying the material properties of both the projectile and target for the five single plate penetration equations. The calculated results for a 2017 aluminum projectile and a 2024-T3 aluminum target are shown on table 1. The results were plotted on diameter versus velocity graphs for ballistic and spallation limits using Cricket Graph software, for velocities ranging from 2 to 15 km/s (as defined for orbital debris in reference 7) with several different thicknesses, i.e., 0.040 in (0. 106 cm), 0.050 in (0. 127 cm), 0.080 in (0.203 cm), and 0. l 00 in (0.254 cm) for 2024-T3 and 6061-T6 aluminum targets. Figures l and 2 show the results for ballistic and spallation limits for a 6061-T6 target 0.040-in (0.106-cm) thick. To show the variation with target density, figures 3 and 4 show the results for ballistic and spallation limits for a 2024-T3 aluminum target.

As discussed before, these five equations were derived from test results, with velocities ranging up to 8 km/s. Therefore, the predicted values for the projectile's mass and diameter above 8 km/s are currently impossible to verify by experiment.

Table 1. Calculations of projectile diameters and masses using five single plate penetration equations.

BALLISTIC OR SPALLATION LIMITS (2-15 KM/SEC.)
2017 AL Projectile and 2024-T3 AL Target

Ballistic Limit (B) or Spallation Limit (S) ?
B

C1	C2	C3	C4	C5
1.00000	1.00000	1.00000	1.00000	1.00000

Projectile Density
2.79568 gm/c.c.
0.101 lbs./cuin

Target Density
2.79568 gm/c.c.
0.101 lbs./cuin

Young's Modulus
10.7 X10E6 PSI
73.7765 X GPa

Wall Thickness
0.040 Inch
0.1016 cm

Speed of sound
5.13681502 km/sec

BH
120

Tensile Strength
59 KSI

Vel. km/s	Fish-Summers		Schmidt-Holsapple		JSC (new)		Rockwell (Apollo)		JSC (Apollo)	
	Mass, gm	Dia, cm	Dia, cm	Mass, gm	Dia, cm	Mass, gm	Dia, cm	Mass, gm	Dia, cm	Mass, gm
2.00	8.175E-04	8.235E-02	9.573E-02	1.284E-03	7.710E-02	6.708E-04	7.798E-02	6.941E-04	6.878E-02	4.763E-04
3.00	2.984E-04	5.885E-02	7.906E-02	7.233E-04	5.968E-02	3.111E-04	6.091E-02	3.308E-04	5.318E-02	2.202E-04
4.00	1.460E-04	4.637E-02	6.902E-02	4.813E-04	4.976E-02	1.804E-04	5.112E-02	1.956E-04	4.431E-02	1.273E-04
5.00	8.381E-05	3.854E-02	6.212E-02	3.509E-04	4.322E-02	1.182E-04	4.463E-02	1.301E-04	3.846E-02	8.326E-05
6.00	5.327E-05	3.314E-02	5.700E-02	2.711E-04	3.852E-02	8.367E-05	3.994E-02	9.323E-05	3.426E-02	5.885E-05
7.00	3.631E-05	2.916E-02	5.300E-02	2.179E-04	3.495E-02	6.247E-05	3.636E-02	7.035E-05	3.107E-02	4.389E-05
8.00	2.606E-05	2.611E-02	4.976E-02	1.804E-04	3.212E-02	4.851E-05	3.352E-02	5.511E-05	2.854E-02	3.404E-05
9.00	1.944E-05	2.368E-02	4.707E-02	1.527E-04	2.982E-02	3.881E-05	3.120E-02	4.444E-05	2.649E-02	2.720E-05
10.00	1.496E-05	2.170E-02	4.479E-02	1.315E-04	2.790E-02	3.178E-05	2.926E-02	3.666E-05	2.477E-02	2.226E-05
11.00	1.181E-05	2.005E-02	4.282E-02	1.149E-04	2.627E-02	2.653E-05	2.761E-02	3.080E-05	2.332E-02	1.856E-05
12.00	9.510E-06	1.866E-02	4.109E-02	1.016E-04	2.486E-02	2.250E-05	2.618E-02	2.627E-05	2.207E-02	1.573E-05
13.00	7.794E-06	1.746E-02	3.957E-02	9.070E-05	2.364E-02	1.933E-05	2.494E-02	2.270E-05	2.098E-02	1.351E-05
14.00	6.483E-06	1.642E-02	3.821E-02	8.166E-05	2.256E-02	1.680E-05	2.384E-02	1.982E-05	2.001E-02	1.173E-05
15.00	5.461E-06	1.551E-02	3.699E-02	7.406E-05	2.160E-02	1.474E-05	2.285E-02	1.748E-05	1.915E-02	1.029E-05

Figure 1. Penetration resistance (ballistic limit) of single wall structure 6061-T6 aluminum with $t = 0.040$ in.

Figure 2. Penetration resistance (spallation limit) of single wall structure 6061-T6 aluminum with $t = 0.040$ in.
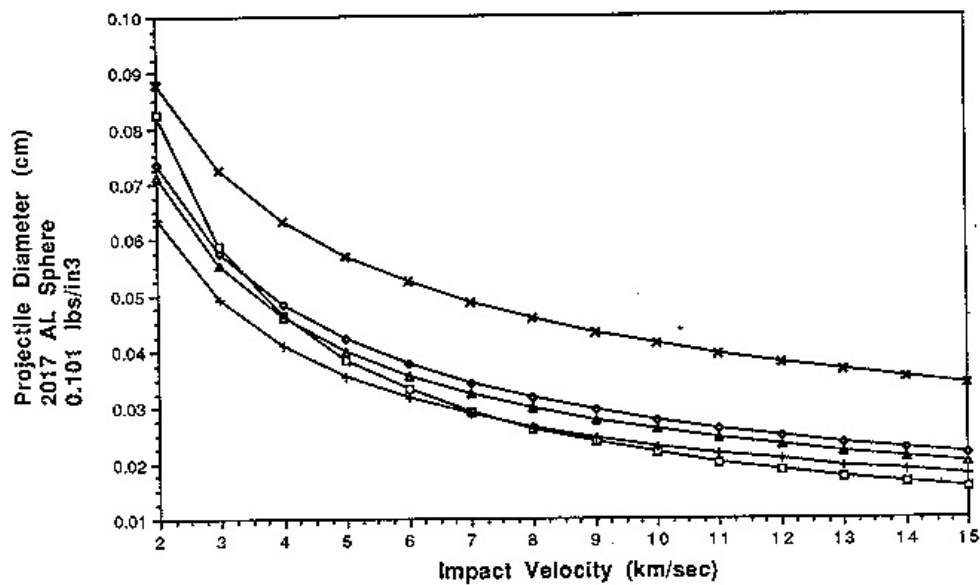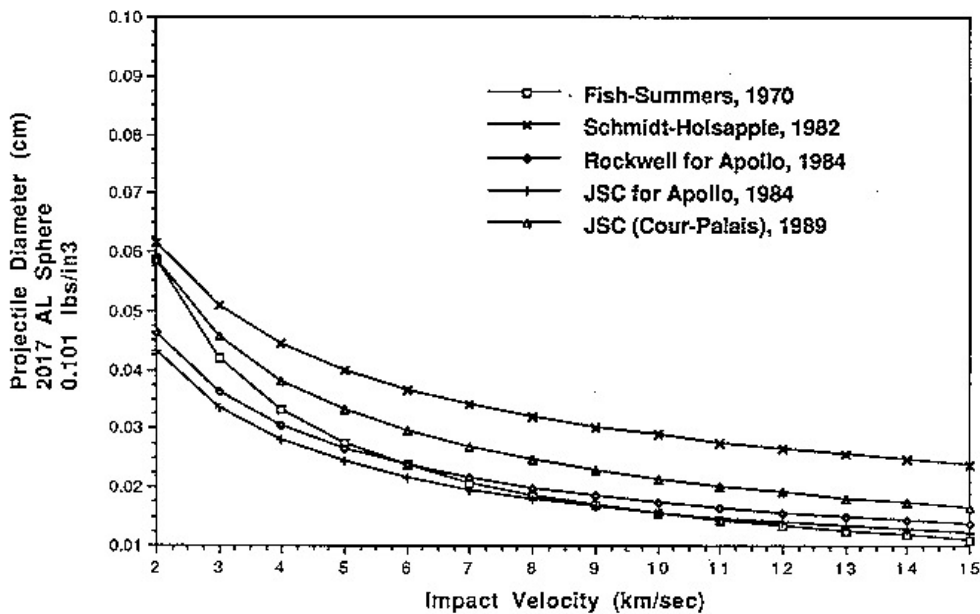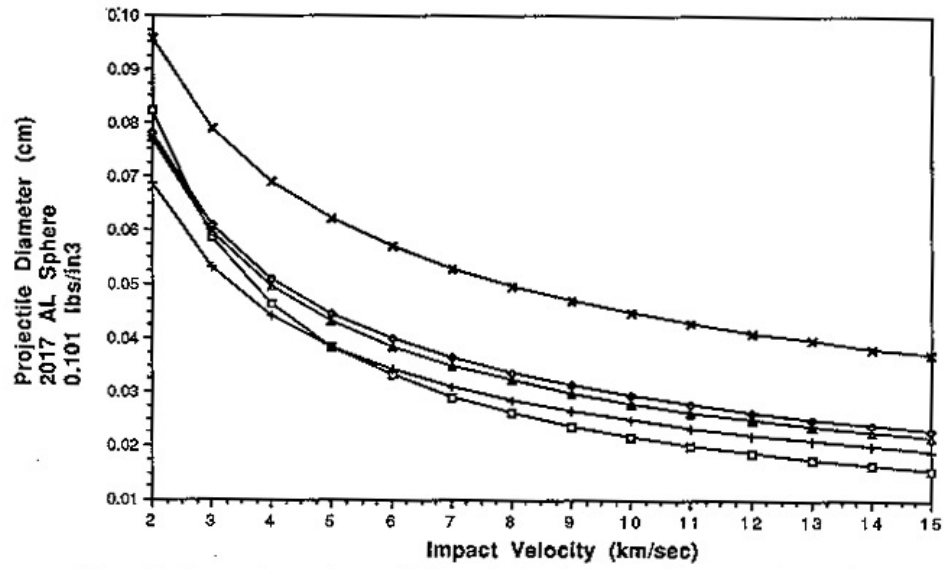
7

Figure 3. Penetration resistance (ballistic limit) of single wall structure 2024-T3 aluminum with $t = 0.040$ in.
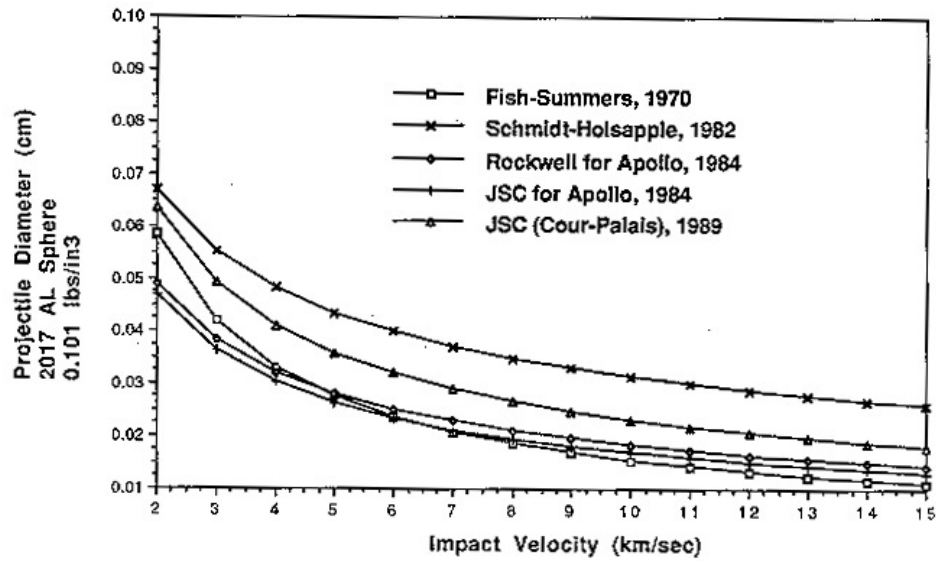

Figure 4. Penetration resistance (spallation limit) of single wall structure 2024-T3 aluminum with $t = 0.040$ in.

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Figure 1 shows the penetration resistance (ballistic limit) of a single-wall structure for the five penetration equations. The Schmidt-Holsapple equation appears to predict the largest values for particle diameters, given an impact velocity. The JSC equation for the Apollo project appears to predict the lowest values for particle diameters, for velocities below 7.5 km/s. Then the Fish-Summers equation predicts the lowest critical diameters for velocities above 7.5 km/s. For the spallation limit (fig. 2), these predictions are nearly the same as for the ballistic limit, except the JSC equation for the Apollo project predicts the lowest critical diameters up to about 9.5 km/s; the Fish-Summers equation yields the lowest values above 9.5 km/s (fig. 2). This behavior is the same for different thicknesses of the same material (6061-T6 Al). In the case of 2024-T6 aluminum for the ballistic limit, figure 3 shows that the Schmidt-Holsapple equation predicts the largest critical diameters; the lowest critical diameters are predicted by the JSC equation for the Apollo project for velocities up to 5 km/s, and by the Fish-Summers equation above 5 km/s. For the spallation limit, as can be seen on figure 4, the JSC equation for the Apollo project predicts the lowest critical diameter up to 6.5 km/s, and the Fish-Summers equation predicts the lowest critical diameter above 6.5 km/s. The other two equations (Rockwell for Apollo and JSC modified Cour-Palais) predict values between the values predicted by these equations. The diameters predicted by the Schmidt-Holsapple are between 1.5 to 2 times larger than the ones predicted by the JSC equation for the Apollo project or Fish-Summers for the 2024-T3 aluminum. Therefore, based on spherical projectiles, the masses predicted by the Schmidt-Holsapple equation are 4 to 7 times larger than predicted by the JSC equation for the Apollo project or the Fish-Summers equation.

The current environment defines an average debris density as an aluminum density, i.e.,2.8gm/cc. There are many people that believe the use of different aluminum alloys as the projectile can cause a big difference in the ballistic limit. Figures 5 through 9 show each equation with various aluminum alloy projectile densities for the ballistic limit, for a 6061-T6 aluminum target with 0.050-in (0.127-cm) thickness. There is a significant difference in impact effects by various projectile materials, but not by various alloys of
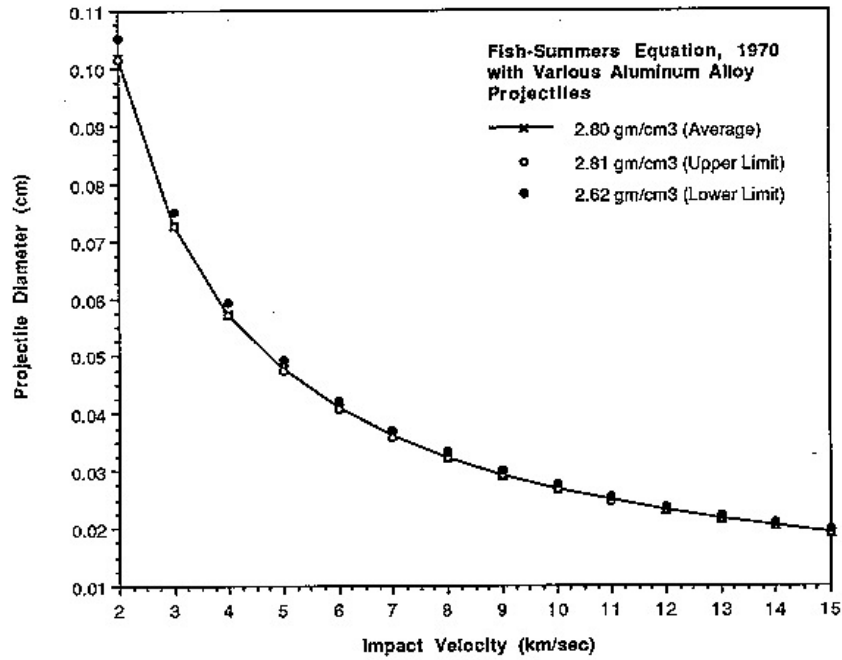
the same material. These figures show that using various aluminum alloy densities will have about 2.6- to 3.5-percent difference in the predicted projectile diameters. Each equation is affected very little by changes in the projectile density, thus these equations predict very little effect on impact damage for projectiles of these similar materials. In fact, even the calculated differences may fall within the scatter of the test data. Projectiles of dissimilar materials, however, would be expected to show significant differences in the predicted critical diameters.

3.2   Comparisons With Test Results

Nineteen hypervelocity impact tests of single plate aluminum shields were performed at JSC for the Marshall Space Flight Center (MSFC) (table 2).

Two out of 19 tests used 2017 aluminum alloy for the projectile, and the rest used 1100 aluminum alloy. The projectile diameters ranged from 0.0156 in (0.0396 cm) to 0.0625 in (0.1588 cm), and the projectile velocities ranged from 5.20 to 7.48 km/s. Two materials (2024-T3 and 6061-T6) were used for the single wall (target), with thicknesses varying from 0.040 in (0.102 cm) to 0.190 in (0.483 cm).

Results from 14 of the tests (groups 1 through 4 from table 2) were compared with the predicted values of the five single plate penetration equations. These tests consisted of two alloys of aluminum targets (2024-T3 and 6061-T6) and two different thicknesses per alloy: 0.040 in (0.102 cm) and 0.063 in (0.160 cm) for 2024-T3, and 0.050 in (0.127 cm) and 0.080 in (0.203 cm) for 6061-T6. Figures 10 through 13 show the test results for each condition.

Fish-Summers Equation, 1970
with Various Aluminum Alloy
Projectiles

— x — 2.80 gm/cm3 (Average)
○ 2.81 gm/cm3 (Upper Limit)
● 2.62 gm/cm3 (Lower Limit)

	Fish- Summers		1970
Velocity	Projectile	Diameter	cm
km/sec	2.62 gm/cm3	2.80 gm/cm3	2.81 gm/cm3
2	0.10502	0.10165	0.10147
3	0.07506	0.07265	0.07252
4	0.05914	0.05724	0.05714
5	0.04915	0.04758	0.04749
6	0.04226	0.04090	0.04083
7	0.03719	0.03600	0.03594
8	0.03330	0.03223	0.03217
9	0.03020	0.02923	0.02918
10	0.02768	0.02679	0.02674
11	0.02558	0.02475	0.02471
12	0.02380	0.02303	0.02299
13	0.02227	0.02155	0.02152
14	0.02094	0.02027	0.02024
15	0.01978	0.01914	0.01911

Figure 5. Penetration resistance (ballistic limit) of single wall structure 6061-T6 aluminum with $t = 0.050$ in. Comparison of aluminum alloy projectile densities with Fish-Summers equation..

10
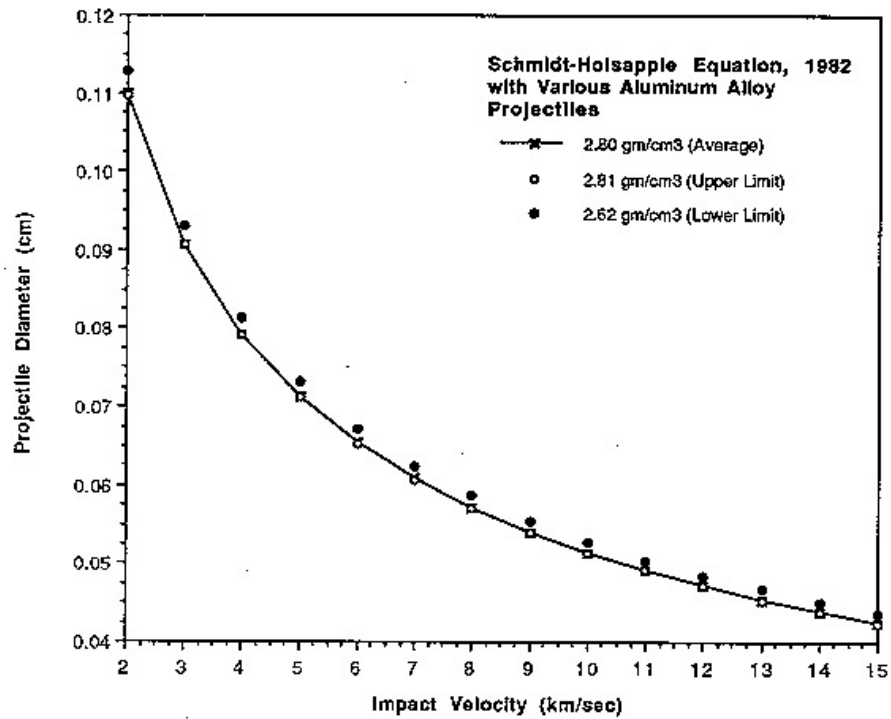
Schmidt-Holsapple 1982			
Velocity	Projectile Diameter		cm
km/sec	2.62 gm/cm3	2.80 gm/cm3	2.81 gm/cm3
2	0.11277	0.10985	0.10969
3	0.09313	0.09071	0.09059
4	0.08130	0.07920	0.07908
5	0.07317	0.07128	0.07118
6	0.06714	0.06540	0.06531
7	0.06243	0.06081	0.06073
8	0.05862	0.05710	0.05702
9	0.05545	0.05401	0.05393
10	0.05276	0.05139	0.05132
11	0.05044	0.04913	0.04906
12	0.04841	0.04715	0.04709
13	0.04661	0.04540	0.04534
14	0.04501	0.04384	0.04378
15	0.04357	0.04244	0.04238

Figure 6. Penetration resistance (ballistic limit) of single wall structure 6061-T6 aluminum with $t = 0.050$ in. Comparison of aluminum alloy projectile densities with Schmidt-Holsapple equation.

Figure 7. Penetration resistance (ballistic limit) of single wall structure 6061-T6 aluminum with
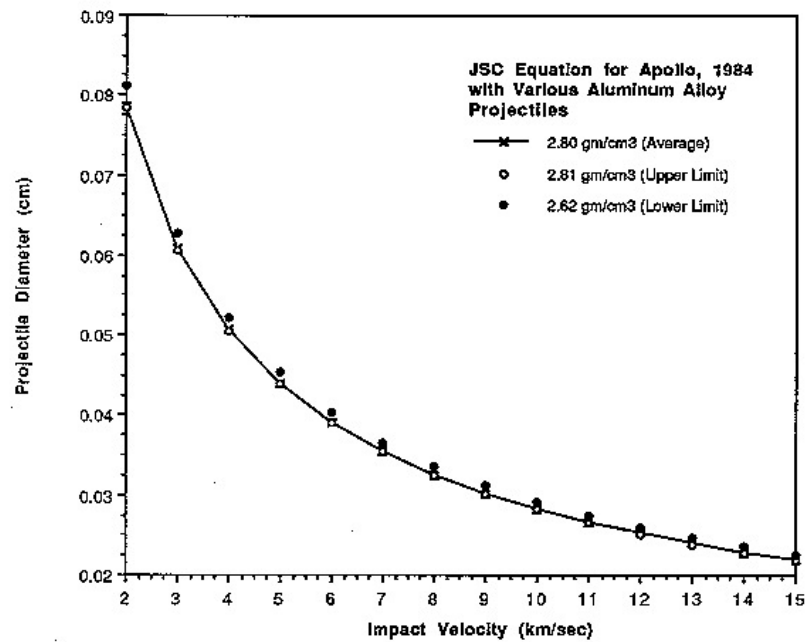$t = 0.050$ in. Comparison of aluminum alloy projectile densities
with Rockwell equation for Apollo.
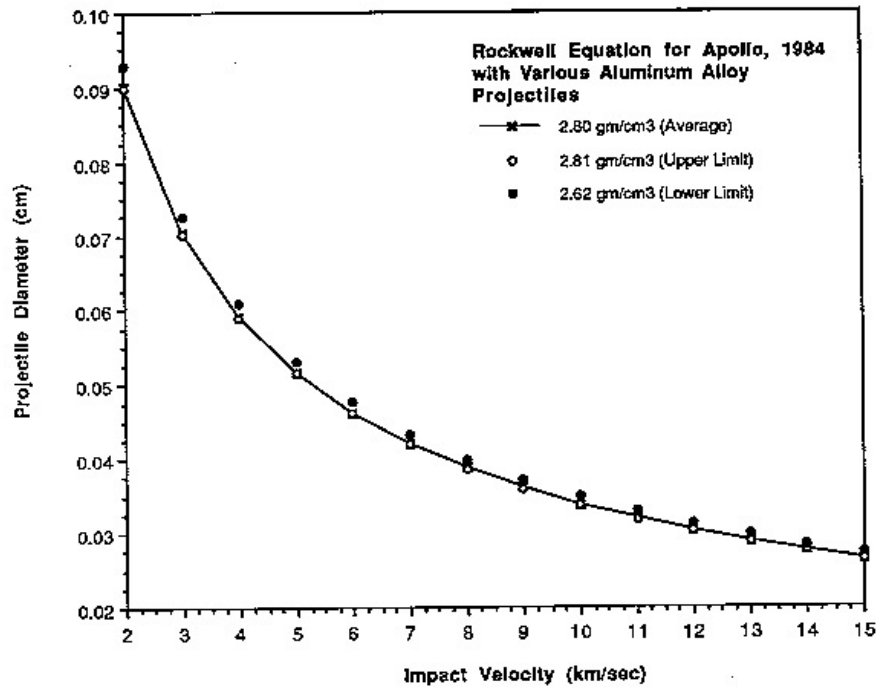
Rockwell for Apollo 1984		
Velocity	Projectile Diameter	cm
km/sec	2.62 gm/cm3	2.80 gm/cm3	2.81 gm/cm3
2	0.09286	0.09010	0.08995
3	0.07254	0.07038	0.07027
4	0.06088	0.05907	0.05897
5	0.05314	0.05156	0.05148
6	0.04756	0.04614	0.04607
7	0.04330	0.04201	0.04194
8	0.03991	0.03873	0.03866
9	0.03715	0.03605	0.03599
10	0.03484	0.03381	0.03375
11	0.03288	0.03190	0.03185
12	0.03118	0.03025	0.03020
13	0.02970	0.02881	0.02877
14	0.02839	0.02754	0.02750
15	0.02722	0.02641	0.02636

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JSC Equation for Apollo, 1984
with Various Aluminum Alloy
Projectiles
2.80 gm/cm3 (Average)
2.81 gm/cm3 (Upper Limit)
2.62 gm/cm3 (Lower Limit)
Projectile Diameter (cm)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Impact Velocity (km/sec)

JSC for Apollo 1984			
Velocity	Projectile Diameter cm		
km/sec	2.62 gm/cm3	2.80 gm/cm3	2.81 gm/cm3
2	0.08103	0.07852	0.07839
3	0.06265	0.06071	0.06061
4	0.05220	0.05058	0.05050
5	0.04531	0.04391	0.04383
6	0.04036	0.03911	0.03904
7	0.03660	0.03547	0.03541
8	0.03363	0.03258	0.03253
9	0.03120	0.03024	0.03019
10	0.02919	0.02828	0.02824
11	0.02747	0.02662	0.02658
12	0.02600	0.02519	0.02515
13	0.02471	0.02395	0.02391
14	0.02358	0.02285	0.02281
15	0.02257	0.02187	0.02183

Figure 8. Penetration resistance (ballistic limit) of single wall structure 6061-T6 aluminum with t = 0.050 in. Comparison of aluminum alloy projectile densities with JSC equation for Apollo.
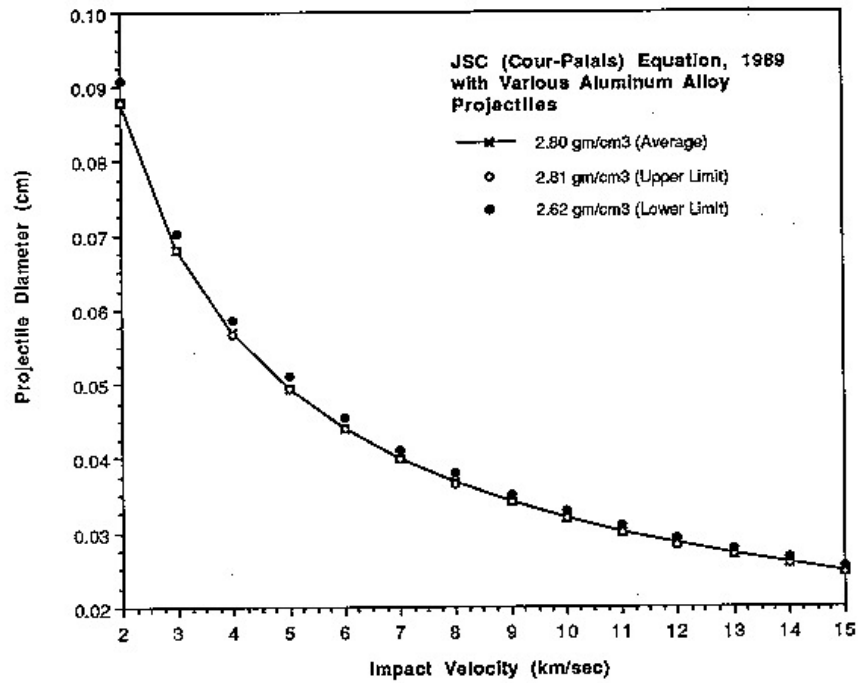
JSC, Cour -Palais		1989	
Velocity	**Projectile Diameter**	cm	
km/sec	2.62 gm/cm3	2.80 gm/cm3	2.81 gm/cm3
2	0.09082	0.08800	0.08786
3	0.07030	0.06812	0.06801
4	0.05862	0.05680	0.05671
5	0.05091	0.04934	0.04925
6	0.04538	0.04397	0.04390
7	0.04117	0.03989	0.03982
8	0.03784	0.03667	0.03660
9	0.03513	0.03404	0.03398
10	0.03286	0.03185	0.03179
11	0.03094	0.02999	0.02993
12	0.02929	0.02838	0.02833
13	0.02785	0.02698	0.02694
14	0.02657	0.02575	0.02571
15	0.02544	0.02465	0.02461

Figure 9. Penetration resistance (ballistic limit) of single wall structure 6061-T6 aluminum with $t = 0.050$ in. Comparison of aluminum alloy projectile densities with JSC (Cour-Palais) equation.

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Table 2. Test results from JSC for single plate.

Group	Item No.	Shot Number	Velocity (km/sec)	Projectiles Material	Dia. (in.)	Dia. (cm)	Targets Material	t (in.)	t (cm)	Penetration (Y/N)	Comments
1	1	1198	6.74	1100	0.01563	0.03969	6061-T6	0.050	0.12700	YES	Near Ballistic Limit
	2	1238	6.78	1100	0.01563	0.03969	6061-T6	0.050	0.12700	No	Near Ballistic Limit
	3	1222	6.81	1100	0.01563	0.03969	6061-T6	0.050	0.12700	Yes	Near Ballistic Limit
	4	1226	7.18	1100	0.01563	0.03969	6061-T6	0.050	0.12700	Yes	Near Ballistic Limit
	5	1236	est. 7.48	1100	0.01563	0.03969	6061-T6	0.050	0.12700	Yes	Near Ballistic Limit
	6	1220	7.49	1100	0.01563	0.03969	6061-T6	0.050	0.12700	Yes	Near Ballistic Limit
2	7	1268	5.2	1100	0.01563	0.03969	2024-T3	0.063	0.16002	No	
	8	1197	6.63	1100	0.01563	0.03969	2024-T3	0.063	0.16002	No	
3	9	1195	5.47	1100	0.01563	0.03969	6061-T6	0.080	0.20320	No	
	10	1227	6.81	1100	0.01563	0.03969	6061-T6	0.080	0.20320	No	
	11	1254	7.18	1100	0.01563	0.03969	6061-T6	0.080	0.20320	No	
	12	1247	7.34	1100	0.01563	0.03969	6061-T6	0.080	0.20320	No	
4	13	1191	6.53	1100	0.03125	0.07938	2024-T3	0.040	0.10160	Yes	
	14	1192	7	1100	0.03125	0.07938	2024-T3	0.040	0.10160	Yes	
5	15	1196	6.60	1100	0.01563	0.03969	2024-T3	0.080	0.20320	No	
	16	1203	7.34	1100	0.03125	0.07938	6061-T6	0.080	0.20320	No	
	17	A909	6.86	2017	0.03125	0.07938	6061-T6	0.125	0.31750	No	Near Spallation Limit
	18	A908	7.12	2017	0.03125	0.07938	6061-T6	0.190	0.48260	No	
	19	A894	7.02	1100	0.06250	0.15875	6061-T6	0.190	0.48260	Yes	

Note : Group 1 - Projectile Diameter = 0.01563", Target Material = 6061-T6, t = 0.050"
2 - Projectile Diameter = 0.01563", Target Material = 2024-T3, t = 0.063"
3 - Projectile Diameter = 0.01563", Target Material = 6061-T6, t = 0.080"
4 - Projectile Diameter = 0.03125", Target Material = 2024-T3, t = 0.040"

All five equations predicted the penetration that resulted from the tests using 2024-T3 aluminum targets with 0.040-in (0.102-cm) thickness (fig. 10). Also, all five equations predicted the nonpenetrations that resulted using 2024-T3 aluminum targets with 0.063-in (0.160-cm) thickness (fig. 11). For each of these two cases, only two data points were available from the tests, and the projectile's size used were too far away from the ballistic limit curve to make any conclusions of the equations' accuracies. Four of the equations, all but the Schmidt-Holsapple equation, correctly predicted the no penetration results of four tests which used 6061-T6 aluminum targets with 0.080 in (0.203-cm) thickness (fig. 12) and incorrectly predicted a penetration would occur for the fifth test (No. 1203). The Schmidt-Holsapple equation correctly predicted that all five of the tests would result in incomplete target penetration. Again there is not enough test data to determine the effectiveness of these equations.

Finally, as shown on figure 13, two equations (Rockwell for Apollo and Schmidt-Holsapple) incorrectly predict five of the six tests for the aluminum target 6061-T6 with 0.050-in (0. 127-cm) plate thickness. The Fish-Summers equation and JSC (Apollo) equation, on the other hand, correctly predict five of the six tests, with test No. 1238 being the incorrectly predicted penetration. By looking at figure 13, one can expect that the ballistic limit might exist somewhere between the modified Cour-Palais and Fish-Summers equations, but additional tests are required to verify this.

4.   RECOMMENDATIONS/CONCLUSIONS

In the previous section, the five single plate penetration equations were compared to each other and with test results. As seen in section 3.1, these equations predict a wide range of projectile diameters at a given velocity. Thus it is very difficult to choose the "right" prediction equation. The thickness of the single plate could have a large variation by choosing a different penetration equation.

One can save much weight by choosing the most unconservative equation, which underestimates the value for the penetrating projectile diameter. Therefore, the cost can be reduced signifi-

cantly, but this choice could result in unforeseen critical damage to the spacecraft or loss of the entire spacecraft. On the other hand, one can design a conservative, well-protected spacecraft, but the spacecraft could become very heavy. Thus, the launch and material costs would be increased.

Even though all five equations are empirically developed with various materials, and especially for aluminum alloys, one cannot be confident in the shield design with the predictions obtained by the penetration equations, without verifying by tests. Therefore, it is recommended that designed shields should be tested with the actual configuration, and realistic velocities and materials for projectiles, to prove the design will act as predicted, when impacted by a meteoroid or debris particle. Only then can the design be declared acceptable for orbital operations.
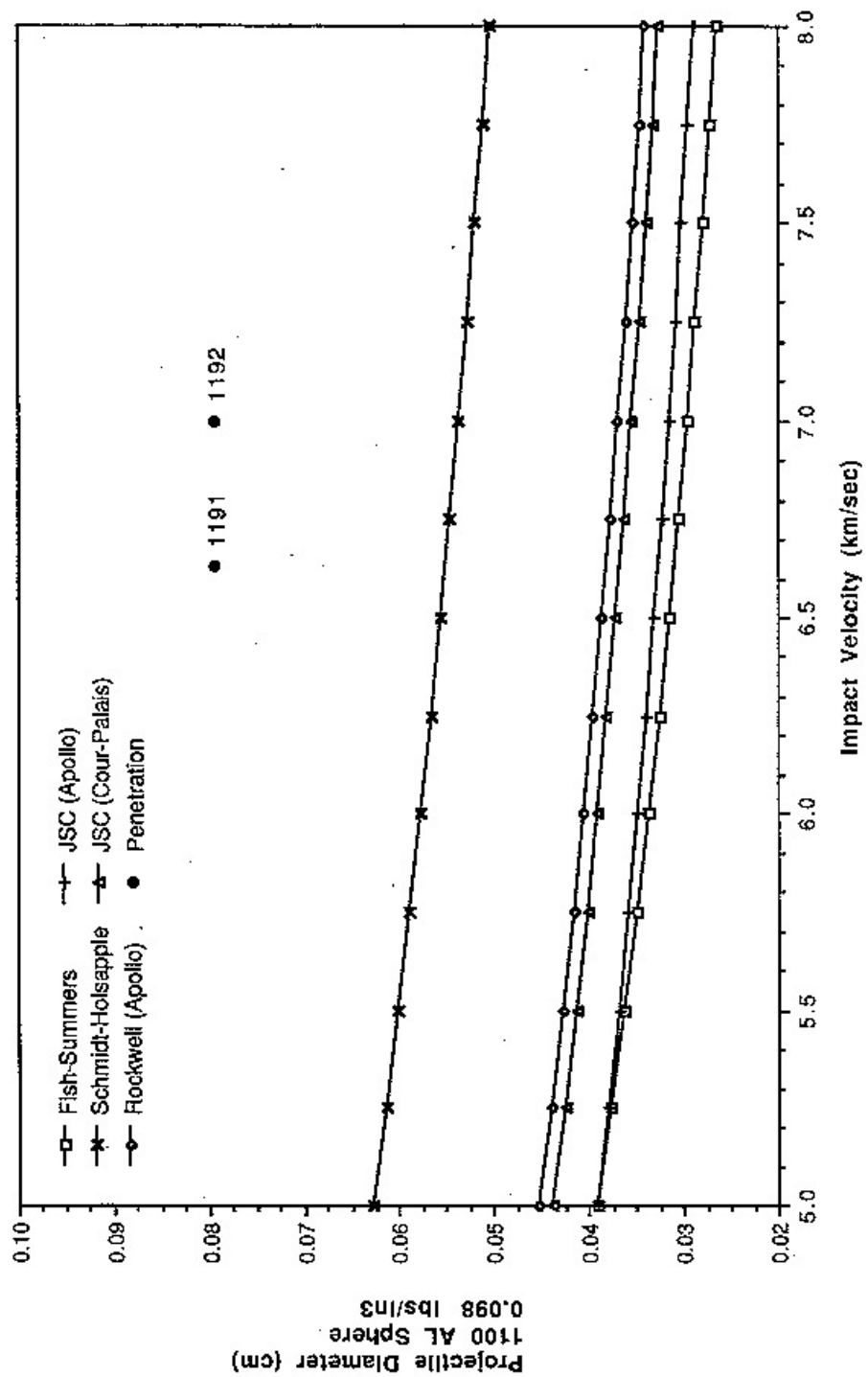
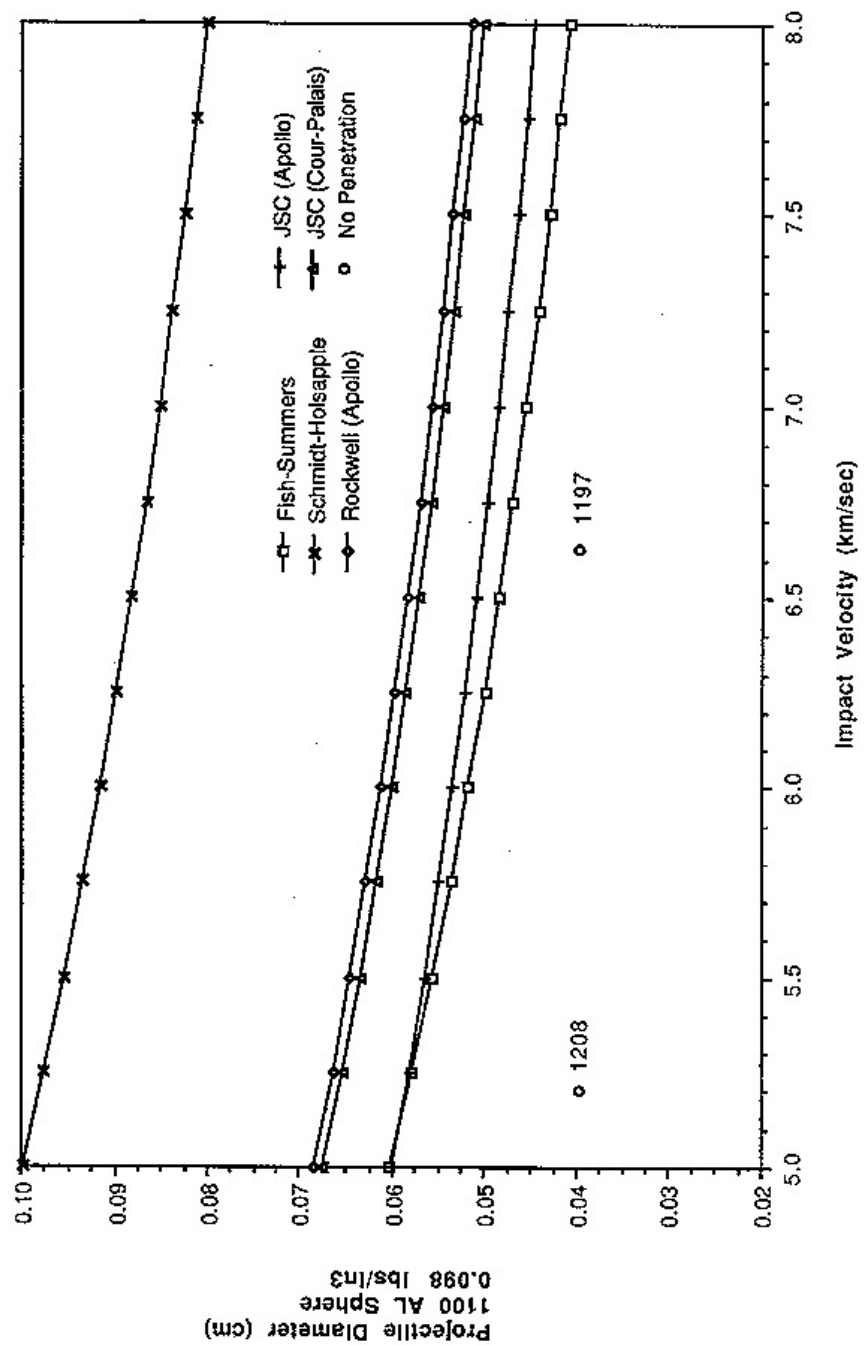Figure 10. Single wall penetration equations (ballistic limit) using 2024-T3 aluminum target with $t = 0.040$ in.

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Figure 11. Single wall penetration equations (ballistic limit) using 2024-T3 aluminum target with $t = 0.063$ in.
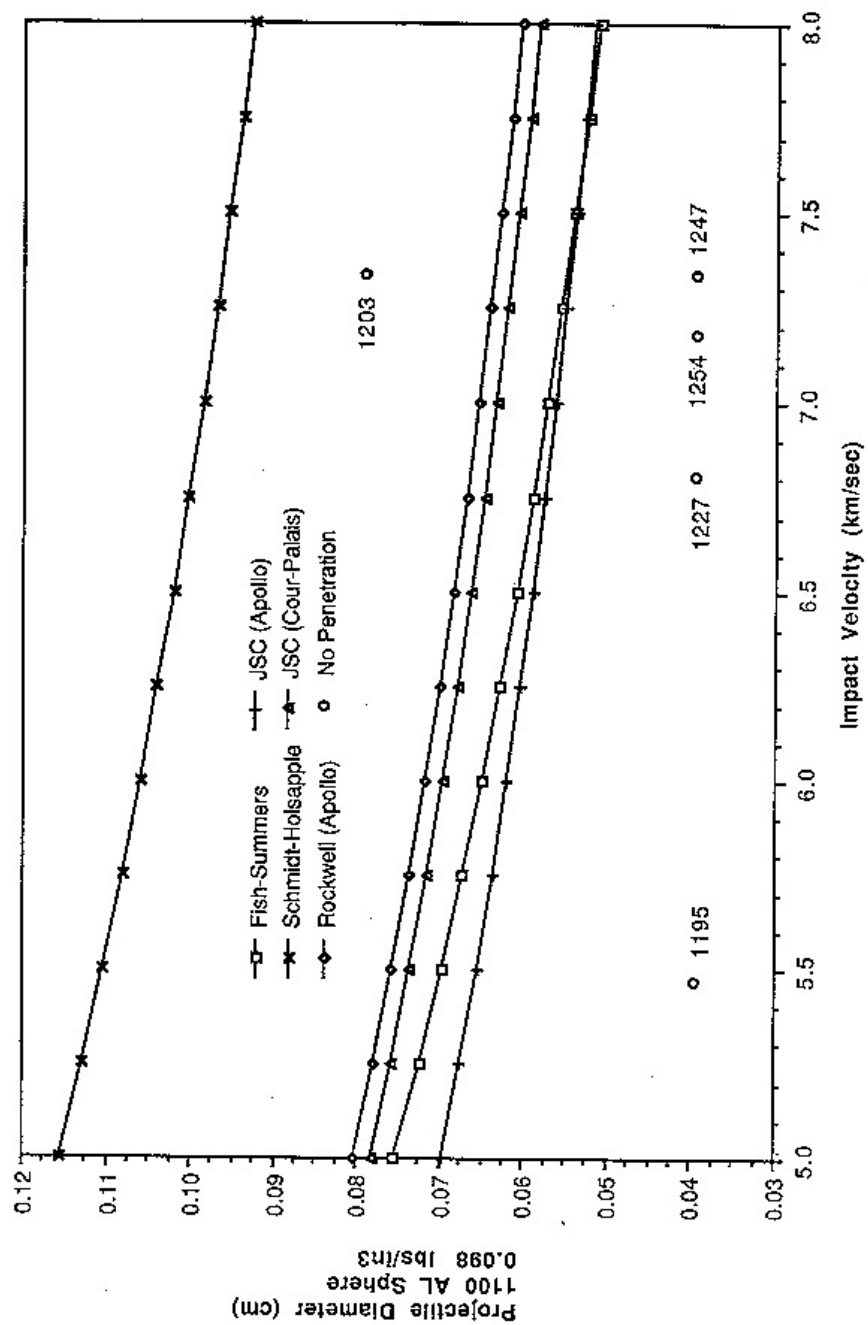
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Figure 12. Single wall penetration equations (ballistic limit) using 6061-T6 aluminum target with $t = 0.080$ in.
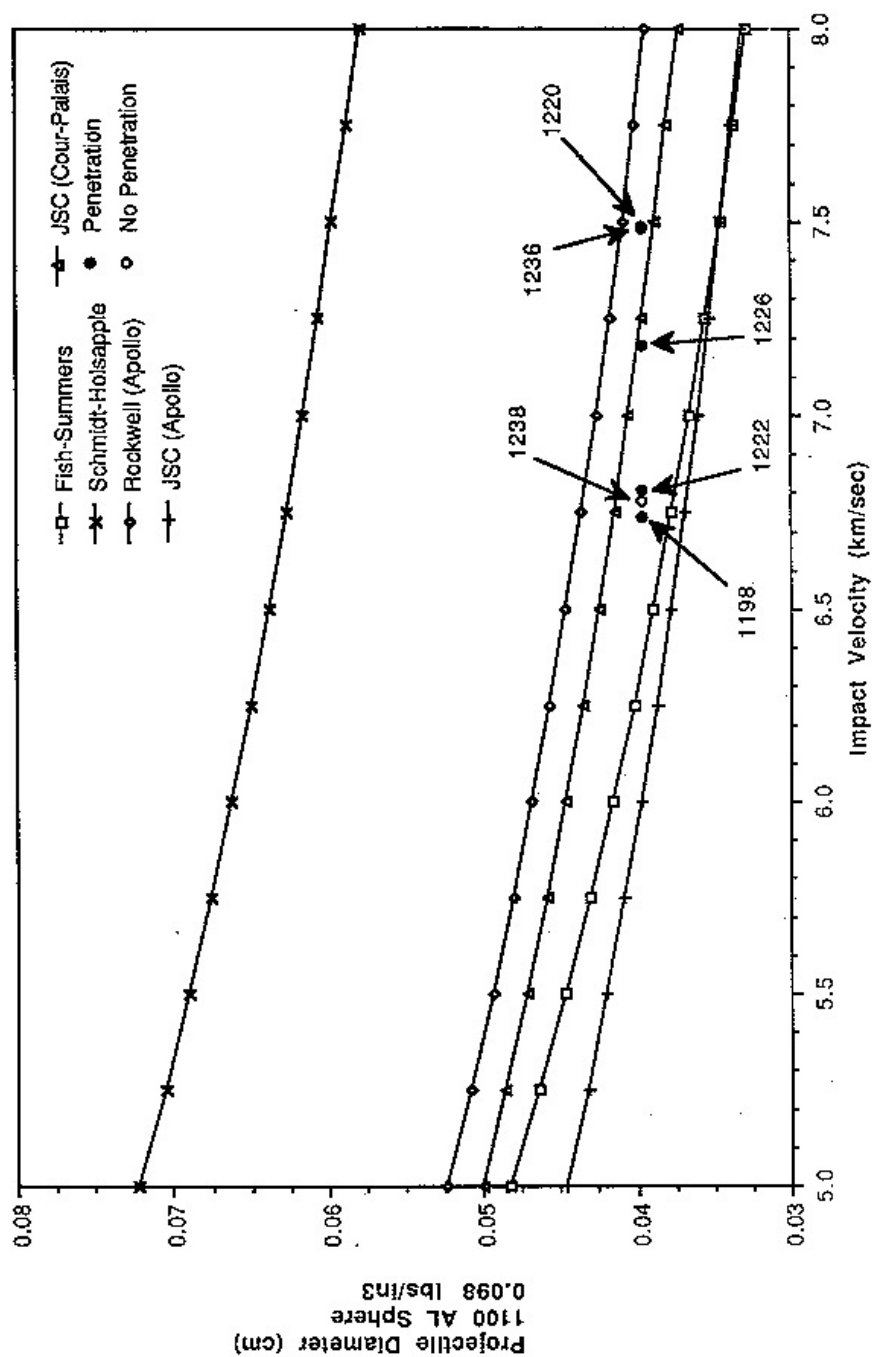
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Figure 13. Single wall penetration equations (ballistic limit) using 6061-T6 aluminum target with $t = 0.050$ in.

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APPROVAL

SINGLE WALL PENETRATION EQUATIONS

By K.B. Hayashida and J.H. Robinson

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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